SIMULATION OF FUEL CELL FOR

RENEWABLE ENERGY SYSTEM

A thesis submitted for the partial fulfilment of the requirement for the bachelor degree in electrical engineering technology

By

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CERTIFICATE

This is to certify that the thesis entitled ' **Simulation of Fuel Cell for renewable energy system'** submitted by **Ibadahun Pathaw (108EE084)** in the partial fulfilment of the requirement for the degree of **Bachelor of Technology** in **Electrical Engineering,** National Institute of Technology, Rourkela, is an authentic work carried out by her under my supervision. To the best of my knowledge the matter embodied in the thesis has not been submitted to any other universities/institute for award of any degree or diploma.

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INTRODUCTION

A fuel cell is a device that converts the chemical energy from the fuel cell to electrical energy. The principle of fuel cell was first introduce by German scientist Christian Friedrich Schonbein in 1838. A typical fuel cell produces a voltage from 0.6 to 0.7 volts at full rated. Fuel cell uses hydrogen as a fuel and it has a high energy conversion efficiency. Fuel cell mostly have electrical efficiencies to upto 60% electrical efficiency. A fuel cell resembles a fuel cell in many aspects but in case of a fuel cell it can supply electricity for a longer period of time and it also has the advantage as it is not required to recharged except that the amount of hydrogen have to be maintain. Fuel cell have come into use in many aspects in this modern world as a form of renewable and unexhaustable energy suppy. It has been installed in places such as hospitals, utility plant and many other uses. The use of fuel cell in the production of electricl automobile have open up new scopes in the research program in this field. The fuel cell gain its popularity in this world use after its use in space satellites for suppy of electricity. The work in the field of fuel cell is still in progress till date.

OBJECTIVE:

The research of the Modeling of PEMFC (Proton Exchange Membrane Fuel Cell) is mostly based on the fundamentals of the chemical reactions or other equations. This paper has been prepared by me as per my project for the numerical simulation of a fuel cell. This paper have been studied inorder to obtained the maximum potential output given from a fuel cell by studying the V – I characteristics obtained from the simulation of the cell from the matlab model and the different simulation are obtained.

CHAPTER 1

INTRODUCTION TO FUEL CELL

Basics of fuel cell

A fuel cell is an electrochemical device and it uses hydrogen as its fuel to produce protons, electrons, heat and a byproduct of water. This technology is commonly based on a simple chemical reaction combustion of hydrogen and air i.e. oxygen. This simple reaction is given below:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (1.1)$$

This chemical reaction between hydrogen and oxygen harnessed electrons which can provide electricity through a simple connected circuit provided with a load. The area of contact between the electrolyte, the electrode and the hydrogen fuel is very small, due to this there is a high resistance between the electrodes in the electrolyte. These problems in a fuel cell have been corrected by proper designing of a flat plate electrodes and a small thickness of electrolyte between the electrodes which gives a maximum area of contact between the electrolyte, electrodes and hydrogen which helps in achieving maximum efficiency of the fuel cell.

A fuel cell can produce electricity as long as hydrogen fuel is supplied constantly to the cell. Its design is based on the simple arrangement of two electrodes placing opposite to the electrolyte. Hydrogen and oxygen reaction through the electrolyte by means of a simple chemical reaction in which electricity is produce through the load along with heat and byproduct of water. Thus this cell donot require any external recharging of the battery.

In the electrodes the hydrogen is supplied to the negative terminal known as the anode and the oxygen is supplied to the positive of the terminal known as the cathode. When the chemical reaction is in the process hydrogen is divided to produce both electrons and protons. These are transferred to the cathode in two different paths, the electrons passes through the load which is away from the

electrolyte through a simple circuit consisting of a load which can produce electricity for that load while the protons passes through the electrolyte and then re-combine with the electrons in the cathode. Thus this recombination of proton electron with oxygen present in the cathode produces a harmless byproduct of water. This hydrogen fuel can be optained from hydrocarbon, methanol and natural gas. Since electricity is produce through a chemical reaction thus it is cleaner than production based on combustion of fuels.

History

Sir William Robert Grove (1811-1896) gives the origin of the fuel cell technology. He studied at Oxford University in chemistry and has the official patent right for the development of a fuel cell. In 1838, Grove developed the wet-cell battery. With his knowledge in chemistry and electrolysis he knows that electricity can split water into two gasses i.e. hydrogen and water so he approached to a conclusion that if the opposite reaction is performed then electricity can be produce. This is the first gas battery produced by Grove which later came to be known as fuel cell.

Ludwig Mond (1839-1909), with assistant Carl Langer experimented with a fuel cell to to produce 6amps per square feet at 0.73volts.

Friedrich Wilhelm Ostwald (1853-1932),is the founder in the field of physical chemistry. He worked on the relationship of the components of the fuel cell such as the electrodes, the electrolyte ,hydrogen, oxygen, electrons and the protons

Emil Baur (1873-1944), researched in the area of high temperature fuel cell. This device used molten silver as its electrolyte.

Francis Thomas Bacon (1904-1992), developed a fuel cell which uses nickel electrodes at a pressure of 3000*psi*. His work was use in World War II and his fuel cell was used by the Royal Navy Submarines. Bacon’s developments was lincensed and used by the Apollo spacecraft fuel cellwhich is still bein used till date in spacecraft.

Future of fuel cell technology

In the present world, where all means of power has been exploited by men for meeting the global need of the power a new power source with energy efficient, low pollutant and unlimited supply of fuel for power production is required. Thus fuel cell which consist all this criteria is developed which can now accomplish the global power needs with effective efficiency and environmental securities. Due to their low operating temperature, fast start ups and ecological friendly constraints fuel cell can be use in the future for distributed generation of power for the production of energy and thus they are set to be the power source of the future. The decreasing use of fossil fuels in the form of production of power due to its severe effects on the environment ecological status in the past few decades, has lead to an increase in the use of fuel cell used as a substitute of fossil fuels. Due to this demand in the production of fuel cell technology, fuel cells is now at a high level of development status. Fuel cell can produce power in the range of 1watt to 10 megawatt.

Applications of fuel cell

The applications of fuel cells depends on the type of cell used and its rating. Small rating fuel cell can be used in cell phones, laptops and other personal computers and other type of personal electronic equipment. Fuel cell with rating of 1KW to 100 KW can be used for power automobiles for domestic as well as military used and for used in public transportation. Rating ranging from 1MW to 10 MW fuel cell can be used for large scale power generation in grid distributed power generation for quality AC source. Currently, a major advanced research is in the field of fuel cell for power vehicles to create a vehicle that would remove the dependence of modern automobiles from any mechanical systems. Thus this electronic car with minimum moving parts will decrease the causes of failure in a car. Another advantage of fuel cell over other batteries is also due to the fact that fuel cell does not need to be recharged but have to be refueled and also the power densities of fuel cell is higher than any other commercialized batteries. The per area power production of fuel cell is large so small fuel cell can be used for the same power which inturns reduced the size and

space needed for the construction of the cell. Fuel cell in large scale production can be used to increase the current efficiency for wind turbine power plant. This is done by transferring the hot exhaust of the fuel cell to the turbine which then increases the efficiency of that turbine to about 80%. These applications of the fuel cell has thus lead the technology to a higher level as the demands for it increases and subsequently lead to the better and efficient production of the fuel cell.

CHAPTER 2

THERMODYNAMICS OF A FUEL CELL

Overview of the laws of thermodynamics

Thermodynamics is the study of conversion of energy in a given electrochemical system. Thermodynamics laws governs the changes in all such systems which are mostly based on experience. These laws can predict the changes that cdan occur in the system but still they cannot predict the preciseness of the rate, and the changes that can occur. The thermodynamics initially was concerned only with the relation between mechanical work and the heat produce during the industrial revolution. Later it was realised that if the moving parts are minimum in a system then the workdone by the particular system can be increase which then lead to the development of the concept of chemical thermodynamics. The fuel cell also is completely based entirely on the first and second laws of thermodynamics and its applications. Review of these laws of thermodynamics is given below.

First law of thermodynamics :

This law also refer to as the law of conservation of energy states that " energy can neither be created nor destroyed but it can only be transferred from one form to the other." i.e the total energy available in the system does not change but the form in which it is present or available can change. Mathematically it is represented as :

$$dE = Q - W \quad (1)$$

where E is the energy of the sytem, Q is the heat input into the system, and W is the workdone by the system. An open system is a system which allows both mass and energy transfer. A fuel cell ia an open system as it allows both mass and energy flow through its boundaries.

For an open sytem, energy change can be expressed as in the following equation:

$$\Delta E = \Delta U + \Delta KE + \Delta PE + \Delta(PV) \quad (2)$$

Where U being the internal energy of the system, KE and PE refers as the kinetic and potential energy present in the system, PV is the pressure-volume workdone on the fluid. Another term known as the enthalpy of the system (H) combines the internal energy with the workdone of the system as in the following equation:

$$H = U + PV \quad (3)$$

From equation 2 and 3, the change in energy in an open system can be written as :

$$\Delta H = Q - W \quad (4)$$

This equation works only for steady flow conditions, i.e ΔKE and $\Delta PE = 0$.

Applications of first law of thermodynamics in a fuel cell :

The simple combustion reaction which takes place in a fuel cell is:

$$\text{Fuel} + \text{Oxidant} = \text{Product} \quad (5)$$

This is an electrochemical reaction which involves the electrons transfer from one electrode to the other. The number of electrons transfered depends on the stoishiometry of the fuel being oxidised as here in a fuel cell it is hydrogen. The amount of electricity is given by the equivalent chemical change of an electron and is given by the equation:

$$F = Ae \quad (6)$$

Where F is the Faraday's constant which is equal to 96493 coulombs, e is the electrons charge equal to 1.6×10^{-19} , and A is the Avagadro's number equal to 6.023×10^{23}. Thus from the above equation we can say that the amount of electricity that occurs when equation (6) occurs is :

$$\text{Electricity} = NF \quad (7)$$

Here N, is the number of electrons being transfered and the electrical workdone in the reaction due to the transfer of the electron is :

$$W = - NFE \quad (8)$$

E is the potential difference between the two electrode (cell voltage). Negative sign has no significance but it just indicates that work is being done in the system. Now putting equation (8) in equation (4) we have :

$$\Delta H = Q - NFE \quad (9)$$

Second law of thermodynamics :

In the first law of thermodynamics it only states about the conservation of the total energy and it does not say anything about the direction of the flow of energy transfer and we know that heat is transfer only from a hot body to a cold body. Thus the shortcomings of the first law is corrected here in the second law of thermodynamics. Second law of thermodynamics can be stated as " the total entropy of the system cannot be decrease other than by increasing the entropy of some other system." Entropy is the measure of the disorderliness of the system.

Reversible process and the concept of entropy of the system:

A system undergoes a reversible change as even when it passes from initial state to the final state it remains in equilibrium with the environment. An irreversible process generates entropy can be made into a reversible process by reducing the temperature gradient from finite to infinite temperature difference. Entropy is given by the equation:

$$\Delta S = (\Delta Q / T)_{rev} \quad (10)$$

Where S is the measure of the entropy of the system, Q is the frictional heat loss or heat transfer, T is the temperature of the system. Also it is said that entropy is a reversible process, therefore

$$\Delta S_{total} = \Delta S_{system} + \Delta S_{surrounding} \geq 0 \quad (11)$$

Application of the second law of thermopdynamics and the Gibbs free energy:

From the equation (9) we have,

$$\Delta H = Q - NFE$$

We can put $Q = T\Delta S$ as it is obtained from the equaton of the entropy of the fuel cell i.e,

$$\Delta H = T\Delta S - NFE \quad (12)$$

In differential form it can be written as ,

$$\Delta H = TdS - FEdN \quad (13)$$

As it is a reversible process workdone is maximum and it is given by Gibbs free energy (G)

$$\Delta G = - FEdN \quad (14)$$

Putting equation (14) in (13), we have

$$\Delta G = \Delta H - T\Delta S \quad (15)$$

By understanding equation (15), it can be said that the change in entropy and the change in enthalpy of the system at a constant temperature can influence the development of free energy as free energy is mainly due to the exixtence of the independence mass in the internal of the system so from this we can write that,

$$\Delta U = \Delta Q - \Delta W \quad (16)$$

$$\Delta U = T\Delta S - P\Delta V + \Sigma \mu i \Delta ni \quad (17)$$

Where μ_i is refer as the chemical potential is the independent masses and n_i is the amount of masses present in the internal of the fuel cell that carries the free energy. The product of these is done which shows the workdone of the masses and the summation is to include all the masses. Thus we have,

$$\Delta H = \Delta U + P\Delta V \quad (18)$$

Put equation (17) in (18) we have,

$$dH = TdS + \Sigma \mu i dn_i \quad (19)$$

now combining equation (13), (14) and (19) we have,

$$\Delta G = \Delta \mu_i \Delta n_i \quad (20)$$

The Nerst equation :

The chemical potential is an intrinsic quantity it helps in the production of the potential energy and it carries the relation between the reactant and the product and it also gives the relation between the Gibbs free energy and the chemical potential species in the internal of the system. Thus we have the following relation for Gibbs free energy,

$$G = H - TS \quad (21)$$

$$\Delta G = \Delta H - T\Delta S - S\Delta T \quad (22)$$

Since , $H = U + PV,$

$$\Delta H = \Delta U + P\Delta V + V\Delta P$$

Therefore,

$$\Delta G = \Delta U + P\Delta V + V\Delta P - T\Delta S - S\Delta T \quad (23)$$

Put ΔU fron equation (17),

$$\Delta G = T\Delta S - P\Delta V + \Sigma \mu i \Delta ni + P\Delta V + V\Delta P - T\Delta S - S\Delta T \quad (24)$$

Which then becomes,

$$\Delta G = VdP - S\Delta T + \Sigma \mu i \Delta ni \quad (25)$$

Differentiating equation (25) w.r.t P we have,

$$(\delta G/\delta P)\ T, n = V \quad (26)$$

Considering ideal gases we have,

$$V = nRT / P \quad (27)$$

Combining equations (26) , (27) we have,

$$(\delta G/\delta P)\ T, n = nRT / P \quad (28)$$

$$\Delta G = G - G^{o} = nRT \ln (P / P^{o}) \quad (29)$$

Where the subscript represents the standard state of G and P, and from the chemical potential definition we can have,

$$\mu_i = \mu_i^o + RT \ln (P / P^o) \quad (30)$$

now the Gibbs free energy for a given reaction may be written as follows ,

$$\Delta G = \Sigma v_p \mu_p - \Sigma v_r \mu_r \quad (31)$$

Where v is a stoichiometric number and subscripts p and r are the products and the reactants

Since, $\Delta G = - NFE$ (32)

Putting equation (30) in (31) and then combining (31) and (32) we have the equation :

$$\Delta G = \Sigma v_p \mu_p^o - \Sigma v_r \mu_r^o + RT \ln \{\Pi (P_p^{vp} / P_r^{vr})\} = - NFE \quad (33)$$

At a standard state where the reactants and products are at a unit pressure the logarithmic equation is equal to 0 and so thus the above equation reduces to :

$$\Delta G^o = \Sigma v_p \mu_p^o - \Sigma v_r \mu_r^o = - NFE \quad (34)$$

At equilibrium, $\Delta G = 0$ and the logarithmic equal to equilibrium constant K so the above equation can be written as,

$$0 = \Sigma v_p \mu_p^o - \Sigma v_r \mu_r^o + RT \ln K \quad (35)$$

substitute equation (34) in (35) the equilibrium reaction can be written as

$$\Delta G^o = - RT \ln K = - NFE^o \quad (36)$$

Thus now the generalised equation of equation (33) is given as

$$\Delta G = \Delta G^o + RT \ln \{\Pi (P_p^{vp} / P_r^{vr})\} = - NFE \quad (37)$$

Dividing euqtion (37) throughout by NF, we get

$$\Delta G^o / NF + (RT/ NF) \ln \{\Pi (P_p^{vp} / P_r^{vr})\} = - E \quad (38)$$

Now substitute the first term in the left hand side with equation (36), we now have,

$$-E^o + (RT/ NF) \ln \{\Pi (P_p^{vp} / P_r^{vr})\} = - E \quad (39)$$

Thus the above equation can then be arrange as in the following below :

$$E = E^o - (RT/ NF) \ln \{\Pi (P_p^{vp} / P_r^{vr})\} \quad (40)$$

The above equation is refer to as the Nerst equation and is mostly used in the field of electrochemistry for the evaluation of the effect of the changes in the activity of the reactants and the

products and also of the temperature on the cell voltage cell. This Nerst equation is the voltage potential produce by the fuel cell without considering the losses and taking all the components at an ideal values.

CHAPTER 3

POLYMER ELECTROLYTE FUEL CELL (PEMFC)

Introduction

The Proton exchange membrane (PEM) fuel cell is the most commonly use among the polymer and it is also known as the Polymer Electrolyte Membrane Fuel Cell (PEMFC). This fuel cell as it operates at a very low temperature but high power densities even at this temperature it thus reduces the overall volume, weight and cost of the production. PEMFC has non-movable electrolyte membrane so there is simplicity in the process of production and by this it reduces corrosion which in turns leads to longer stack life. The PEM fuel cell is similar to all the other fuel cell as it consist of the major three parts, the anode , cathode and the electrolyte also known as the membrane. The PEM fuel cell are being use in the application of automobiles , busses , portable electronic appliance. Previously due to the use of platinum as a catalyst the use of PEMs are really limited due to the high cost of platinum but now after the introduction of nafion the application of the PEMs are again increasing day by day. Today PEMs have a great hope in the industrial world and in the future it can also be use for the production of distributed power generation. It is potentially one of the most important fuel for energy production that is being researched today.

The Polymer Membrane

The PEM is a solid-state exchange membrane. It was discovered by William Grubbs in the year of 1959, where he discovered that even without the presence of solid in his membrane he was able to transfer electrons and protons to the cathode which was taken care of by NASA and it is still on use till today. The most commonly use membrane is nafion which is produced by DuPont. This membrane is essentially a carbon chain which attached to it are fluorine atoms which is called

Teflon. Nafion allows upto 50% increase in dry weight. This property result in five important properties of the nafion membrane, highly acidic, mechanically strong, acidic, very absorbvative, and good proton conductors.The membrane allows the transfer of protons and the electrons have an external path for its travel. These then meet in the cathode and thus as a by product of this reaction between protons, electrons and oxygen in the cathode water is formed. The PEM fuel cell can run at a temperature less than $80^{o}C$.

Introduction to PEMFC development of the modelling Fuel Cell

Fuel cell converts the chemical energy to the electrical energy by converting oxygen and hydrogen directly into electricity heat and water in an electrochemical sytem process.

PEM fuel cell is mainly based on the basic hydrogen and oxygen combustion reaction given below as: $2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat

The reaction which takes place both in the anode and cathode in the process are:

At anode : $H_2 - 2e \rightarrow 2H^+$

At cathode : $O_2 + 4H^+ \rightarrow 2H_2O$

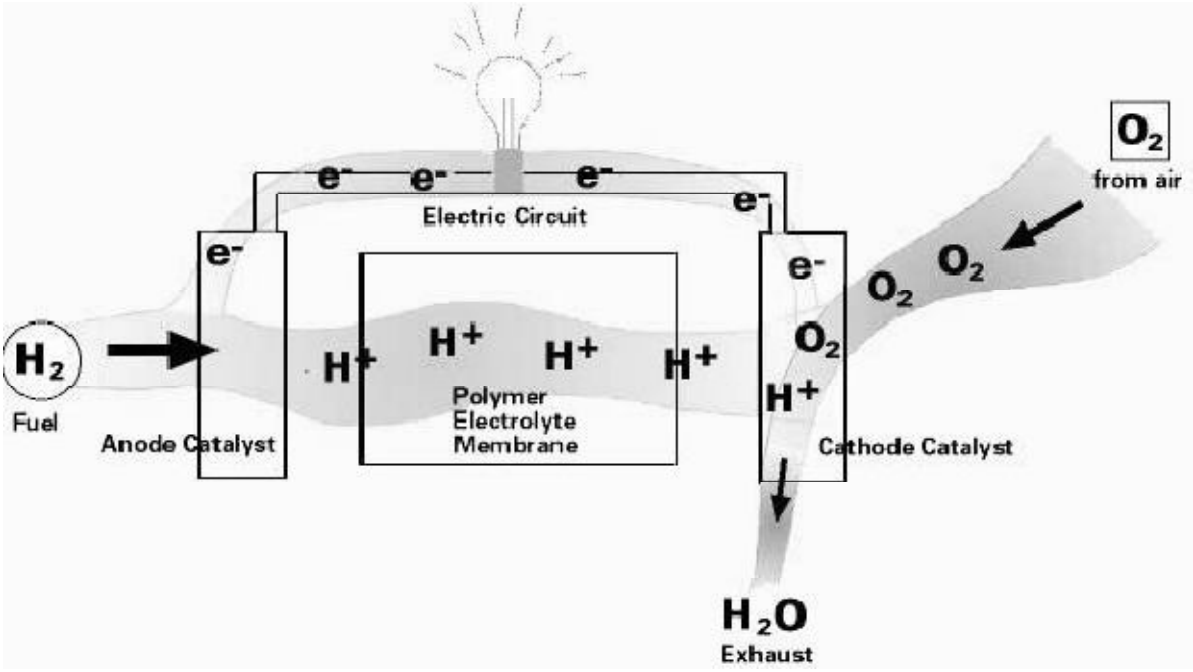


Fig 1 : Basic fuel cell operation

(ref : Introduction to Fuel Cell Technology by Chris Rayment and Scott Sherwin)

A basic diagram of the fuel cell system is shown is fig 1. This figure shows the structure of the PEM. The main elements which has to be considered for the proper working of the system insides are: anode and cathode plates, electrodes and membrane. The electrodes mainly consist of a gas diffusion layer and a catalyst layer. Both layers have a porous, partially hydrophobic, structure. Air is introduced to the cathode side, and hydrogen is introduced through the anode side. The membrane in the central of both the anode and the cathode works as an electrolyte that performs the functions of transferring **H**+ from the anode to the cathode and also perform reactant separation. The important reaction which forms after the completion of these two reaction are as given in the above paragraphs.

Circuit modelling of PEM fuel cell

The V- I characteristics of a typical PEM fuel cell is at room temperature and normal air pressure. Even in a fuel cell model losses are present which causes the cell potential to be lesser than its ideal voltage. These losses which has to be accounted in a fuel cell are:

1. Activation losses.
2. Concentration losses.
3. Ohmic losses.

The voltage output of a fuel cell is given by the Nerst equation which is given by the equation:

$$E = N [E^o - (RT/ nF) \ln \{\Pi (P_p^{vp} / P_r^{vr})\} - L]$$

Where

E stack voltage output

N number of cells in the system

E^o open circuit voltage at atandard temperature and pressure.

RT/ nF tafel slope which is in the range of 0.03 to 0.12 for 24^{o}C. R is the universal gas constant, F is the Faraday's constant, T is the temperature and n is the number of transferred electrons.

P_p^{vp} partial pressure of the product

P_r^{vr} partial pressure of the reactant

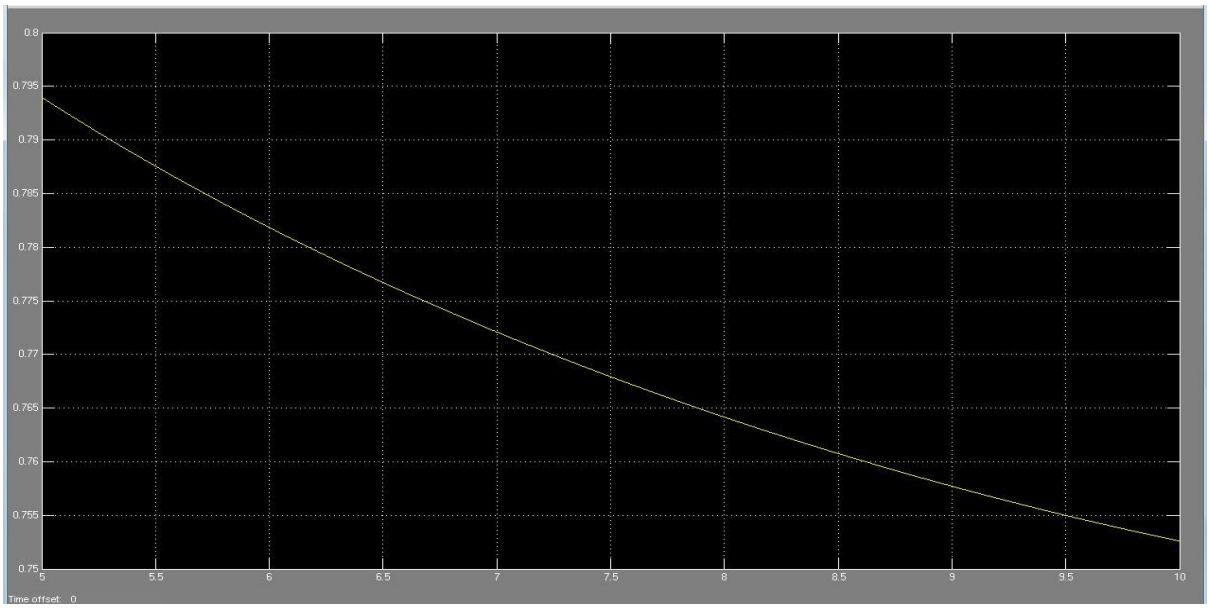
L potential losses.

The PEM fuel cell potential losses contributions to the model are:

- Activation losses – This loss can be reduced by maximizing the catalyst area of contact for the reactions this can be achieve due to the slowness of the reaction that is taking place inside the cell system.

- Ohmic losses – some electrons passing through the load does not reach the cathode this leakage is cause as some of the electrons instead of passing through the load they pass through the membrane so due to this current losses occurs.
- Concentration losses – as the reaction takes place the amount of concentration of reactant in the electrodes decreases due to this concentration loss occurs.

The V-I characteristics accounting for all the losses can be achieve in the matlab/simulink simulation achieve which is given as under.



The above is the simulation of the voltage versus current corve for a 500 W fuel cell used in the study of PEMFC for this project.

CHAPTER 4

MODELING OF THE PROTON EXCHANGE CELL

Introduction

Modelling of the fuel cell is useful for the fuel cell developers so that they can produce better design improvements, cheaper better and efficient fuel cells. Also a good model design of a fuel cell should be able to predict the performance under a wide range of the fuel cell under any operating conditions. Some of the important parameters that should be taken care of in a fuel cell is the system temperature, the fuel and the oxidant temperature, fuel and oxidant pressure, fuel cell potential, and the weight fraction of each reactants. In a fuel cell the assumption taken are:

i. Ideal gas properties

ii. Negligible ohmic potential drops

iii. Incompressible flow

iv. Laminar flow

v. Catalyst layers and diffusion gas layers are considered to be isotropic.

Dynamics modelling of the fuel cell based on chemical fundamentals

In this part a mathematical approach for building of a PEM fuel cell is presented inorder to build a dynamic model for proper analysis and simplification in the fuel cell. The following assumptions has to be taken inorder to build up this model.

1. Ideal and uniformly distributed gases.
2. Constant pressures in the fuel-cell gas flow channels.
3. One dimentionally treated.

4. Humidified hydrogen and oxygen effective anode water vapour pressure is 50% of vapour pressure saturated and the water pressure in the cathode is 100% is to be assume.
5. The reaction product should be in liquid phase and it should work under 100^{o}C.
6. Thermodynamics properties have to be calculated at average stack temperature and all temperature variations inside the stack are neglected, and the overall specific heat is taken to be constant.

The chemical-mechanism model for the output voltage of a single cell can be defined by the following expression:

$$V_{FC} = E_{NERST} - V_{ACT} - V_{OHMIC} - V_{CONC}$$

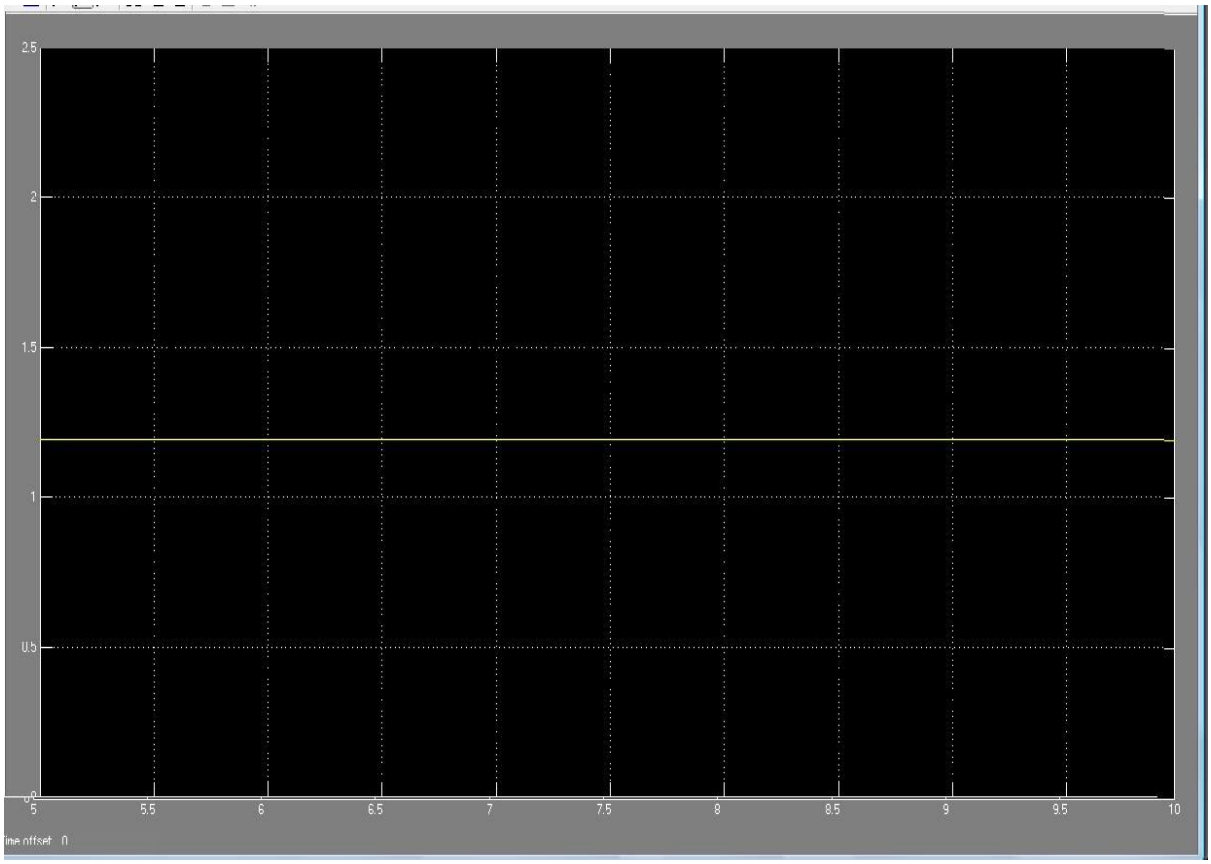
Where V_{FC} is the output voltage of a single cell; E_{NERST} is the electrochemical thermodynamic potential of the cell and it represents its reversible voltage which is an ideal output voltage of the fuel cell; V_{ACT} is the voltage drop due to the activation of the anode and cathodes, or we can call it activation polarization loss; V_{OHMIC} is the ohmic voltage drop, and we can call it ohmic polarization loss; V_{CONC} is the voltage drop resulting from the concentration of reactants, which is the gas transportation loss. Each of the parts mentioned in formula will be discussed below.

Model formulation

Ideal output voltage ENernst

E_{NERST} is the electrochemical thermodynamic potential of the cell and it represents its reversible voltage, which is an ideal output voltage. E_{NERST} can be calculated by a modified version of the Nernst's equation with an extra term to take into account the changes in the temperature with respect to the standard reference temperature 25^{o}C. Using the standard pressure and temperature (SPT) values, we can equate

$$E_{NERST} = 1.229 - 0.85 \times 10^{-3} (T - 298.15) + 4.31 \times 10^{-5} [\ln(P_{h2}) + \tfrac{1}{2} \ln(P_{o2})]$$



Above is the simulation result of the Nerst's equation versus the current input at constant temperature and pressure.

Activation polarization loss

The activation losses are cause due to the slowness of the chemical reactions that are taking place inside the fuel cell as a portion of the voltage produce in the cell is loss or used up during the driving time of the chemical reaction in transferring the electrons and protons from the anode to the cathode and this voltage loss is highly non-linear. The equation for activation overvoltage at standard temperature and pressure is given by :

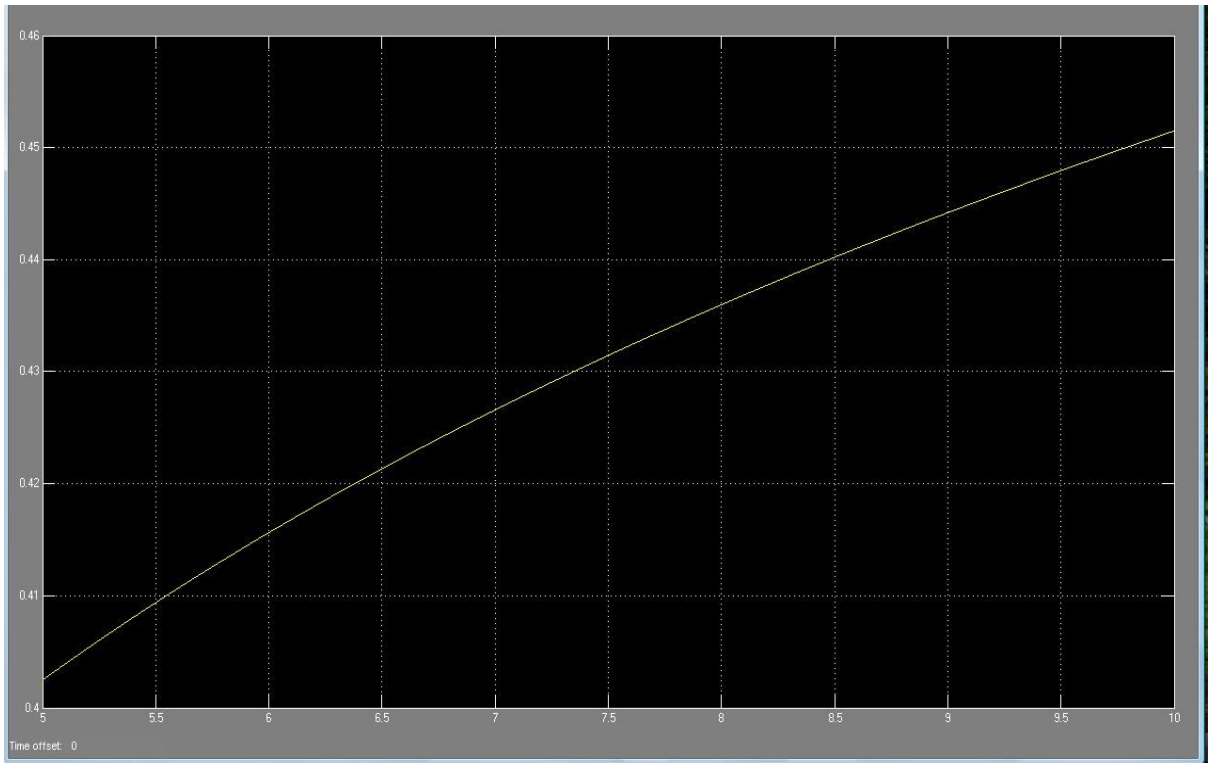
$$V_{act} = - [- 0.948 + (0.00286 + 0.002 \times \ln A + 4.3 \times 10^{-5} \ln (C_{h2})) T + 7.6 \times 10^{-5} T \ln (C_{02}) - 1.93 \times 10^{-4} T \ln(i_{fc})]$$

A is the valid cross-sectional area of membrane. C_{h2} is the concentration of hydrogen in the catalytic interface of anode C_{02} is the concentration of oxygen in the catalytic interface of the cathode (mol/cm3), and the constant values refer to the parametric coefficients for the cell model and again

$$C_{02} = P_{o2} / 5.08 \times 10^6 e^{-498/T}$$

$$C_{h2} = P_{h2} / 5.08 \times 10^6 e^{-498/T}$$

I_{FC} is the operating current.



The simulation of the activation voltage versus the input current is given in the above graph.

Ohmic polarization loss

Ohmic polarization loss results from the inside resistance of the collecting plates and carbon electrodes, and also the resistance of transferring protons through the membrane. Usually, the equivalent resistance can be formed as

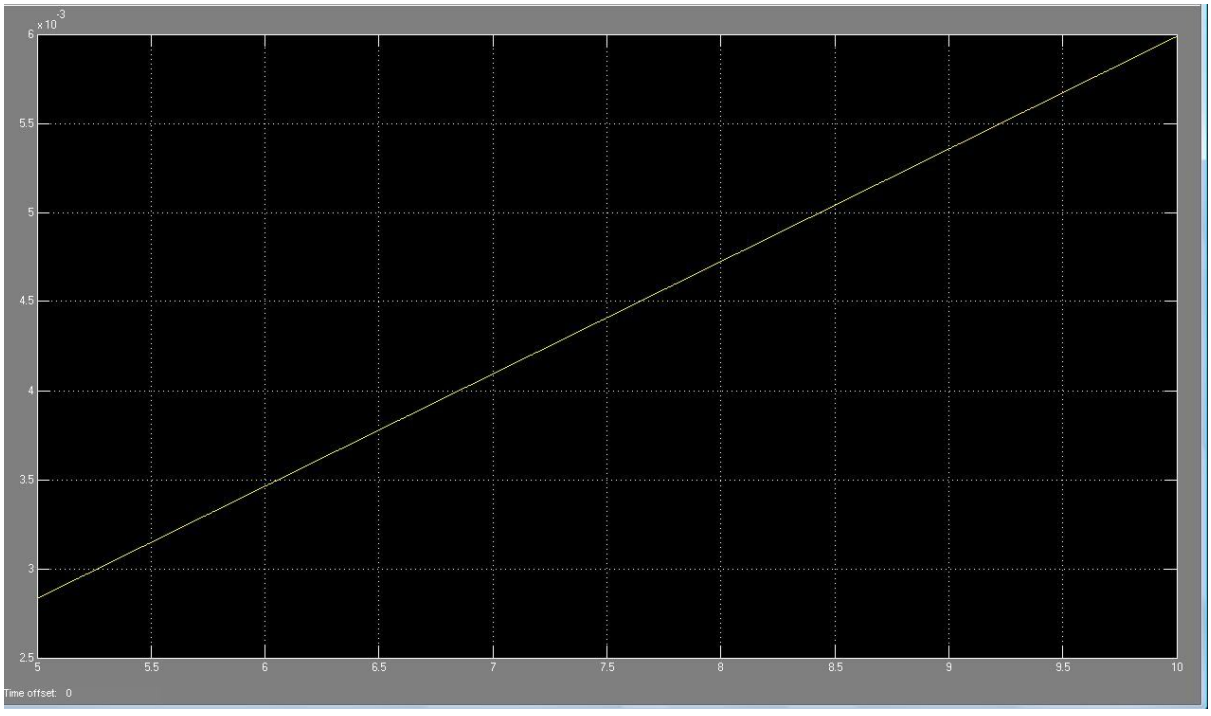
$$R_M = P_M L / A$$

P_M represents the specific resistance of the membrane. A is the area of the electrode membrane, and L is the thickness of the electrodes. We can assume the membrane thickness to be 178×10-4cm. The specific resistance can be represented by:

$$P_M = \frac{181.6\left[1+0.03\left(\frac{i_{fc}}{A}\right)+0.062\left(\frac{T^2}{303^2}\right)\left(\frac{i_{fc}}{A}\right)\text{^}2.5\right]}{\left[\psi-0.634-3\left(\frac{i_{fc}}{A}\right)\right]exp\left[4.18\left(\frac{T-303}{T}\right)\right]}$$

The parameter ψ is an adjustable parameter with a possible maximum value of 23.The loss of the resistance to the transfer of protons through the membrane usually considered constant, as R_C is (0.0003Ω). So the ohmic polarization loss is represented by the equation:

$$V_{ohmic} = i_{fc} (R_M + R_C)$$



The above is the simulation of the ohmic voltage versus the current of the fuel cell.

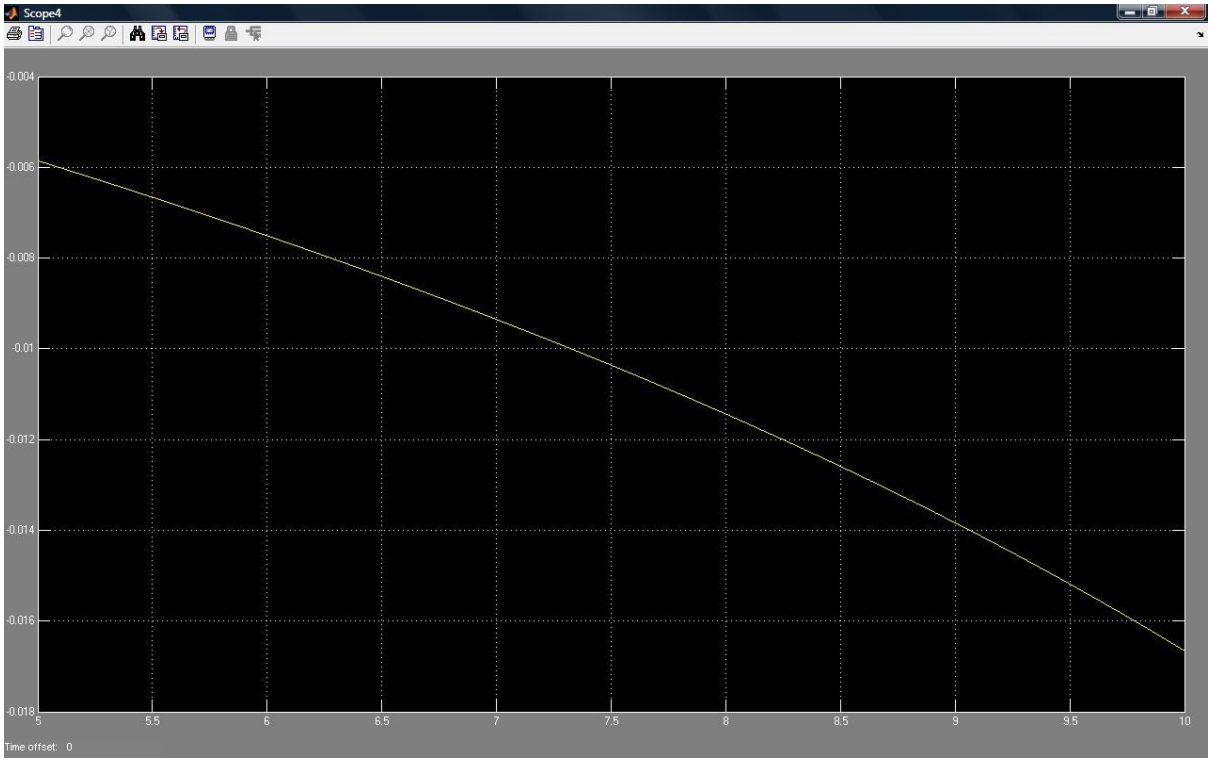
Concentration loss

This loss is cause due to the concentration of the reactants at the surface of the electrodes as fuel is being used up. The equation of the concentration loss is given by :

$$V_{conc} = - B \ln (1- J / J_{max})$$

Where J_{max} is in the range of 500 to 1500 mA/cm2, and B(V) is a parametric coefficient that depends mostly on the cell and its operation state and J represents the actual current density of the cell (A/cm2).

By combining all the losses along with the Nerst's equation we obtained the required model for the fuel cell as given in the matlab/ simulink model attached. This model is simulated and the required simulation for the different voltage losses is obtained in the form of graphs.



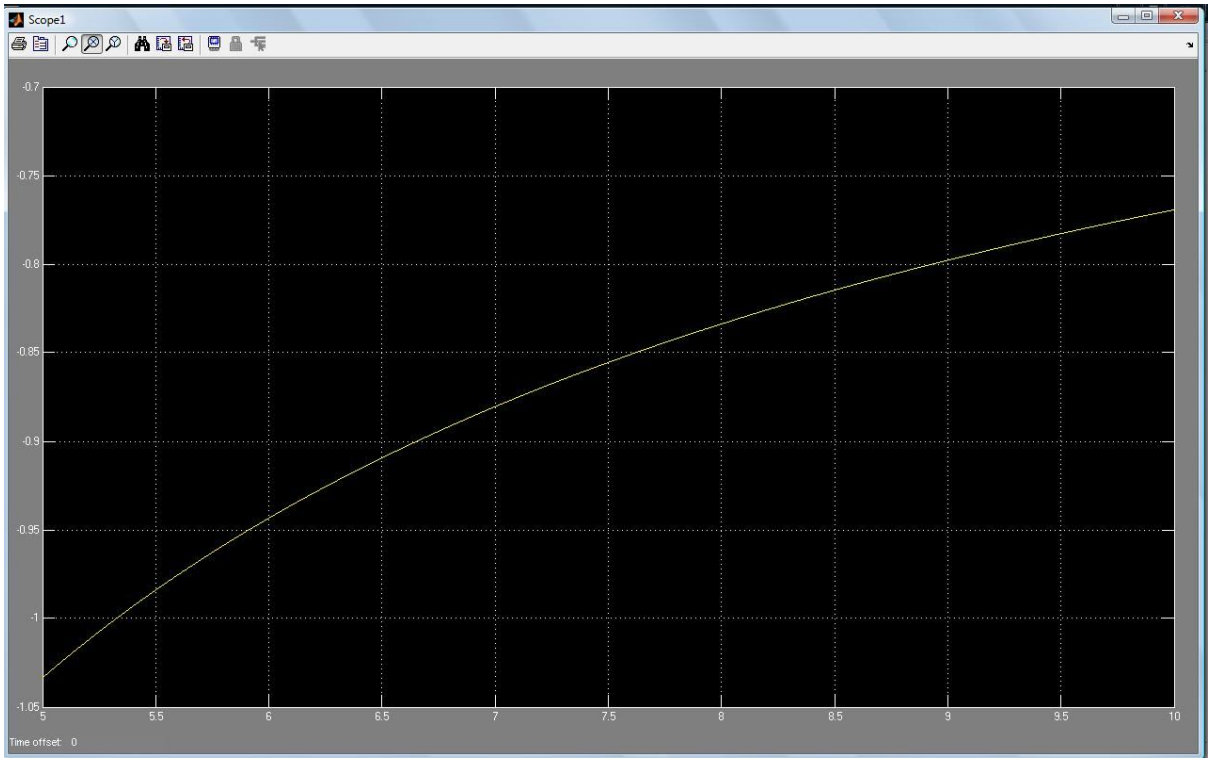
The above simulation gives the graph of the voltage concentration loss versus the input current in the cell.

Double - layer charging effect

In a PEM fuel cell the electrodes are separated by solid membrane which blocks the flow of electrons and allows only the flow of H^+ ions. Here the electrons takes the path through the anode to the cathode through the external load and then reaches the cathode while the protons pass through the

electrolyte and reaches the cathode at the same time with the electrons. Due to this two charged layers of opposite polarity are formed across the boundary between the cathode and the porous membrane. These layers are refer to as the electrochemical double layer which can store electrical energy and thus they behave like a superconductor. The effect of this double – layer capacitor is taken in the form of voltage drop across the activation and concentration resistance and it is given by V_C and this voltage drop does not effect the ohmic resistance in the cell. The equation for this is given by :

$$V_C = \left(I - C\frac{dVC}{dt}\right)(r_{act} + r_{conc})$$



This simulation graph that shows the effect of the double charge capacitor in the fuel cell i.e the capacitor voltage versus the input current.

CONCLUSION

The fuel cell model of 500W can be characterized by performing small signal, steady-state and large-signal measurements. Because the modelling approach fully relies on these measurement results, electrochemical phenomena like temperature dependency, charge double layer and adsorption effects are decisively covered with the current dependent element values. The dynamic behaviour of a fuel cell is a complex phenomenon. The power of a PEM fuel cell also depends on operating conditions such as flow rates, relative humidity and temperature of the gases. Mathematical modelling is very important for understanding this complexity. The models and results of other researchers is compared and evaluated. Results for the V–I characteristic of a fuel cell shows the expected output voltage is dependent on the load current. Dynamic interaction effects within a PEM fuel cell are significant, and detailed modelling for such transient effects is necessary. Using a simple procedure and data obtained from the literature, it is possible to obtain a model for a fuel cell stack. The fuel cells are modelled by using various mathematical equations. As well as base sense of these models was same, more parameters were used in some of them. For example, neglected parameters some mathematical models have been inspected in a dynamic model of fuel cell. Matlab-Simulink model is a comprehensive in model. A PEM fuel cell has been modelled with this model exhaustively using more parameters. Dynamical structure of the model can be obtained to be changed to input parameters as required in this model.The factors in the dynamic behaviour of a PEM fuel cell are the reactant gases humidity change, various load changes and liquid water formation in cathode channel. The effects of these factors could be studied in future works.

REFERENCES

1. Mathematical Models of PEM Fuel Cells by Zehra Ural, Muhsin Tunay Gencoglu.
2. Modelling and simulation using matlab by Colleen Spiegel.
3. Introduction to Fuel Cell Technology; Chris Rayment and Scott Sherwin
4. MATLAB® Documentation (2009), Simpower Systems Demos. The Mathworks, Inc.
5. Thermodynamics of Fuel Cells; Leibhafsky and Cairns, Hoogers, Smith and Van Ness
6. Jeferson M. Corrêa FAF, Luciane N. Canha, Marcelo G. Simões. An Electrochemical-Based Fuel Cell Model Suitable for Electrical Engineering Automation Approach.
7. Andrew T. Stamps EPG. Dynamic modeling of a methanol reformer—PEMFC stack system for analysis and design. Journal of Power Sources. 2006.
8. Barbir F. PEM Fuel Cell Design, Engineering, PEM Fuel Cell Design, Engineering, Modeling and Diagnostic Issues Modeling and Diagnostic Issues.
9. Gonder AAPG-HKJD. PEM Fuel Cell Freeze and Rapid Startup Investigation. Milestone Report.2005.
10. Haiping Xu LK, and XuhuiWen, Member, IEEE. Fuel Cell Power System and High Power DC–DC converter. IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL 19, NO 5, SEPTEMBER 2004.
11. Fuel Cell Systems Explained ,Second Edition, James Larminie, Oxford Brookes University, UK; Andrew Dicks University of Queensland, Australia (Former Principal Scientist, BG Technology, UK)
12. www.google.com ; Wikipedia on fuel cell.
13. J. C. Amphlett, R. F. Mann, B. A. Peppley, P. R. Roberge, and A. Rodrigues, “A model predicting transient responses of proton exchange membrane fuel cells,” *J. Power Sources*, vol. 61, no. 1–2, pp. 183–188, Jul./Aug. 1996.